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THE MECHANICAL PROPERTIES AT 800°, 1000°, AND 1200° F OF TWO SUPERALLOYS UNDER CONSIDERATION FOR USE IN THE SUPERSONIC TRANSPORT

by T. M. Cullen and J. W. Freeman

Prepared under Grant No. NsG-124-61 *by*
UNIVERSITY OF MICHIGAN
Ann Arbor, Mich.
for

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SUMMARY

28312 ABST.

An investigation has been conducted in which the upper temperature of usefulness of two nickel-base superalloys was established within relatively narrow limits for application in the proposed supersonic transport. These alloys, René 41 and Waspaloy, were each studied in two conditions of prior treatment to evaluate the maximum temperature at which they exhibited sufficient levels of creep strength, rupture strength and resistance to the presence of sharp edge-notches for use in the SST.

It has been determined that the upper use temperature of these alloys is limited by their behavior in the presence of sharp edge-notches and stress concentrations. The sharp notches were used to simulate cracks in the materials. The alloys exhibited satisfactory resistance to the notches and the stress concentrations at 800°F but not at 1000° or 1200°F. The sensitivity of the alloys to notches and stress concentrations has been related to their creep resistance in the temperature range from 1000° to 1200°F.

With a few exceptions the creep strength and the rupture strength of the alloys exceeded the minimum requirements for application in the supersonic transport for temperatures up to 1200°F. The alloys in the cold reduced and aged condition showed higher properties than the same materials tested in the annealed and aged condition.

AUTHOR

Use in certain sections of the SST will require materials to withstand prolonged exposure to temperatures of approximately 1200°F. René 41 and Waspaloy in the conditions of prior treatment in which they were tested in this investigation are not considered to be satisfactory for application in the SST at temperatures much above 800°F. It should be recognized that there may be conditions of working and/or heat treatment in which these alloys will not be subject to the limitations found in this investigation. From the opposite point of view, it is possible that other alloys being considered for the SST could be subject to the same low notched specimen rupture life at temperatures where appreciable creep can occur.

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INTRODUCTION

As an outgrowth of a screening program (Ref. 1) designed to evaluate the applicability of superalloy sheet materials to the construction of the trisonic transport a study has been carried out at the University of Michigan to help establish the upper temperature of usefulness of these materials. In order to limit the breadth of the program, two of the more promising alloys of this type, René 41 and Waspaloy, were used in this study. Each of these alloys was tested in two conditions of thermal and mechanical treatment. The creep and rupture properties of the alloys were determined at temperatures from 800° to 1200°F and these properties were used to evaluate the upper temperature of usefulness of the materials.

In the original screening program specimens with ASTM sharp edge-notches were exposed for 1000 hours under a stress of 40,000 psi at various temperatures. These tests were included in the screening program as a measure of the resistance of the materials to unstable crack propagation. During exposure several of the notched specimens failed while other notched specimens of the same alloy survived the exposure. These latter specimens had subsequent tensile properties similar to the unexposed material. The failure of some of the specimens during exposure led to the inclusion in the current program of a number of tests designed to measure the "stress-rupture time" characteristics of specimens containing sharp edge-notches.

The parameters which have been applied to the data for the purpose of arriving at an upper temperature of usefulness were:

1. Stress for rupture in 50,000 hours as obtained by extrapolation of tests out to approximately 3000 hours.

2. Stress to produce 0.1 percent creep in 50,000 hours.

3. Minimum time for rupture of specimens containing the ASTM sharp edge-notch at a stress of 40,000 psi.

These reference parameters were selected because: (1) the aircraft is expected to have an operating life of up to 50,000 hours; (2) the total amount of creep which can be tolerated during the operating life is approximately 0.1 percent; and (3) 40,000 psi is a reasonable compromise for the expected service stresses in the civilian supersonic transport.

EXPERIMENTAL MATERIALS

The alloys used in this investigation were in the form of 0.030-inch thick sheet material. These alloys, René 41 and Waspaloy, were each studied in two conditions of prior treatment. These conditions were as follows:

René 41 - (1) Annealed and aged for 16 hours at 1400°F.
(2) Cold reduced 35 percent and aged for 2 hours at 1500°F.

Waspaloy - (1) Annealed and aged for 16 hours at 1400°F.
(2) Cold reduced 40 percent and aged for 2 hours at 1500°F.

The heat numbers and reported chemical compositions of these materials are listed in Table I.

The materials were received in the annealed condition and in the cold reduced condition. Specimen blanks were cut from the sheets and stamped with an identifying code. These blanks were then aged in an electric furnace prior to being machined into the finished specimens.

EXPERIMENTAL PROCEDURES

The upper temperature of usefulness of the two alloys was studied by tests at 800°, 1000° and 1200°F. The test program involved the use of tensile, creep and stress-rupture tests on both smooth and notched specimens. The great majority of the notched specimens contained the ASTM sharp edge-notch which yields a theoretical elastic stress concentration factor of >20.

Properties in both the longitudinal and transverse directions were measured to avoid misleading results from anisotropy effects which might be present in the alloys.

Test Specimens

Unnotched specimens. - The configuration of the smooth specimens used to measure unnotched properties ($K_t = 1.0$) is shown in Figure 1a. Specimens were prepared from rectangular blocks by milling. Ten specimens were machined at a time, using a fixture to clamp the blanks together and assure accurate alignment throughout the machining operation.

Notched specimens. - A few rupture tests were conducted during the program on specimens which contained notches of intermediate acuities. The geometry of the specimens with K_t's of 1.5, 2.1, 3.1, 5.9 and 9.4 is shown in Figure 1b. In these specimens only the notch root radius was changed to vary the stress concentration factor. The values of the notch root radius for the different K_t's are as follows:

Stress Concentration Factor, K_t	Notch Root Radius inch
1.5	0.250
2.1	0.100
3.1	0.040
5.9	0.010
9.4	0.0036
>20	<0.0007

The majority of the notched specimens tested contained the sharp edge-notch recommended by the ASTM (Ref. 2). The configuration of this specimen is shown in Figure 1c. As was the case with the unnotched specimens, ten blanks were machined at one time, using a second fixture to maintain alignment. The reduced section of the specimen was first milled to size. The notches were then ground almost to size, with an alundum wheel having a 60-degree included angle. The notch root radii for stress concentration factors of 1.5 to 9.4 were lapped to final dimensions. The final radii of the sharp notches were obtained by drawing a sharp carbide tool through the notches. Root radii and net section widths were then measured using a 50X optical comparator.

Creep and Rupture Tests

The creep and stress-rupture tests were conducted in individual University of Michigan creep-testing machines. In these units, the stress is applied through a third-class lever system having a lever arm ratio of about 10 to 1. The specimen was gripped by means of pins passed through each end of the specimen and into holders which fitted into a universal joint-type assembly for uniaxial loading. Heating was provided by a resistance furnace which fitted over the specimen and holder assembly.

Strain measurements were taken on the smooth specimens by means of a modified Martens optical extensometer system. Extensometer bars in pairs were attached to collars clamped onto the gage section of the specimens. Placed between the pairs of extensometer bars were the stems of mirror assemblies which reflected an illuminated scale located about five feet in front of the creep unit. The differential movements of the top and bottom pairs of extensometer bars caused a rotation of the mirrors, which was observed through a telescope mounted next to the illuminated scale. As the specimen elongated, a very small movement of the extensometer rods was magnified by the resulting optical lever and converted into a large change in the reflected scale reading. This system permitted the detection of a specimen strain of about 10 millionths of an inch.

Strain measurements were made as each weight was applied during loading. Creep strain was read periodically through the test. When failure occurred an automatic timer was activated by the fall of the specimen holder measuring the rupture time to one-tenth of an hour.

Three thermocouples were attached to each of the creep and rupture specimens at the center and at either end. All the thermocouples were shielded from direct radiation. Prior to starting a test the furnace was heated to within 50°F of the desired temperature. The specimen was then placed in the hot furnace and brought up to the test temperature and distribution in a period of not more than four hours. ASTM recommended practices were followed in controlling the test temperature and distribution.

Strain measurements were not taken on the notched specimens. The procedures followed for the attainment of the proper test temperature and distribution were the same as those used for the unnotched specimens.

In a number of cases the stressed exposure tests were interrupted before rupture of the specimens. In these cases the furnace was turned off at the required time and the specimen was cooled under load to minimize the effects of creep recovery.

Tensile Tests

All tensile tests were conducted with a 60,000-pound capacity hydraulic tensile machine. Unnotched samples were strained at an approximate strain rate of 0.01-inch per inch per minute up to about 2 percent deformation. The strain rate was then increased to about 0.05-inch per inch per minute until failure. Notched specimens were loaded at a rate of 1000 psi net section stress per second. The test procedures followed those of References 2 and 3.

Strain measurements were made on the unnotched specimens using the extensometer system described previously.

RESULTS AND DISCUSSION

Since each of the alloys used in this investigation was tested in two conditions of thermal and mechanical history the results obtained in the program for each of the materials will be presented and discussed in separate sections.

René 41

The properties of this alloy were evaluated in the annealed and aged condition and in the cold worked 35 percent and aged condition. Smooth and notched specimens ($K_t > 20$) were tested at 800°, 1000° and 1200°F. The properties measured included creep strength, rupture strength and tensile strength as influenced by stressed exposure.

Annealed and Aged Condition. - The results of the stress-rupture time tests on smooth specimens are presented in Table II. The data show that there was very little effect of specimen orientation on properties at either 1000° or 1200°F. These data are presented graphically in Figure 2.

There was a marked tendency for the specimens to fracture at the pinholes or beneath the clamp-on collars used to hold the extensometer rods. The tendency for fracture at the pinholes was particularly pronounced at 1200°F and suggests that René 41 sheets in the annealed and aged condition might be sensitive to mild notches. If this is actually the case it is contrary to the general behavior of this type of alloy (Ref. 4). A sensitivity to mild notches has, however, been shown for materials of this type when tensile tested at elevated temperatures (Ref. 5). The tendency for fracture beneath the collars probably was caused by a compressive stress at this location which raised the effective stress on the specimen at the point beneath the clamp-on collars.

The stress-rupture time curve (Figure 2) for smooth specimens at 1000°F had little slope. The 1000 hour rupture strength at this temperature was approximately 158,000 psi as compared with a tensile strength at the same temperature of 178,000 psi. The smooth specimen rupture data at 1200°F cannot be considered reliable because of the tendency of the specimens to fracture at the pinholes and beneath the extensometer collars.

The results of the notched specimen tests are presented in Table III. At 800°F the specimens survived exposure for 1000 hours at stresses as high as 145,000 psi. This stress represents approximately 95 percent of the notch-tensile strength of the alloy at this temperature. A similar resistance to sharp edge-notches was not evident at 1000° or 1200°F, as is shown in Figure 3. At 1000°F the sharp edge-notch specimens exhibited a relatively flat rupture curve out to approximately 300 hours, at which point the curve broke rather sharply downward. The 1000 hour notch strength at 1000°F represents just over 50 percent of notched specimen tensile strength at this same temperature as compared with over 95 percent at 800°F. At 1200°F the properties are much lower than at 1000°F. At 1200°F the scatter of the results is such that it is impossible to draw any meaningful curve through the data.

Figure 4 shows a graph of minimum creep rate versus stress for the annealed René 41 at 800°, 1000° and 1200°F. The lines drawn through the data at each of the temperatures were approximately parallel to one another. As was the case for the smooth specimen rupture data, no differentiation could be made in the results due to specimen orientation.

Data have been obtained which show the influence of stressed exposure on the room temperature tensile properties of the alloy in the annealed condition. These data are presented in Table IV. Examination of the data shows that stressed exposures at temperatures of up to 1200°F have little influence on subsequent room temperature tensile properties. The only exception to this statement might possibly be the transverse notched specimens exposed at 1200°F. Two specimens exposed at this temperature for 1000 and 2000 hours under stresses of 40 and 60 ksi respectively, showed notch strengths which were 23 and 34 ksi below that exhibited by the unexposed material.

Cold Reduced and Aged Condition. - The creep and stress-rupture results obtained from smooth specimens at 800°, 1000° and 1200°F are given in Table V. As was the case with the alloy in the annealed and aged condition, none of the creep-rupture specimens fractured at 800°F in times up to 2000 hours and at stresses of up to almost 99 percent of the ultimate tensile strength of the material at that temperature. At 1000°F, although the stress-rupture time curves (Figure 5) were relatively flat, there was some stress dependency of the rupture time. At 1200°F this dependency was very evident, as is shown in the stress-rupture time curves of Figure 5. At 1000°F there appeared to be a significant difference in rupture time between longitudinal and transverse specimen orientation. This difference may not be real, however, since the transverse specimens showed a particular affinity for fracturing beneath the extensometer collars. As was stated in the previous section, the specimens were subjected to a small compressive stress at the point of contact with the collars. This slight compressive stress may have acted to raise the effective stress on the specimen at this location, thereby causing premature failure. It should be remembered, however, that specimens taken from the sheet material in a longitudinal orientation were also subjected to this compressive force but did not show the same tendency for failure beneath the collars.

The notched specimen results are tabulated in Table VI and are presented graphically in Figure 6. At 800°F, with one exception, the specimens either fractured on initial loading or survived exposure under stresses as high as 140 ksi for time periods of 1000 or 1200 hours. A transverse specimen did fail in 890 hours under a stress of 135 ksi at 800°F. A longitudinal specimen survived exposure for 1000 hours under a stress of 140 ksi at this same temperature, indicating that specimens taken in the longitudinal direction are somewhat stronger than those taken in the transverse direction. At 1000° and 1200°F the longitudinal notched specimens gave significantly higher results than did the transverse specimens. At 1000°F there was a marked variability in the results. While the cause of this behavior has not been determined it is suggested that the rupture life of the notched specimen is limited by the ductility of the material. Table V shows that the rupture ductility of the smooth specimens in the longitudinal direction is considerably greater than that of the transverse specimens. There is little doubt that the apparent low ductility of the transverse smooth specimens is partly the result of the tendency of these specimens to fracture under the collars. Not all of the specimens fractured beneath the collars, however. If we discount those specimens which did break at this location it is still evident that the transverse specimens had lower rupture ductility than the longitudinal specimens.

The suggestion that the variability of the notched specimen results as well as the difference in the results as a function of specimen orientation was partially the result of the low rupture ductility of the alloy in the cold reduced condition is indirectly confirmed by the minimum creep rate data of Figure 7. These data do not show any significant influence of specimen orientation on the creep resistance of the material and therefore creep resistance, per se, is not the cause of either the scatter in the results or the variation in properties with specimen orientation.

Table VII lists the results obtained in the study of the influence of stressed exposure on the room temperature tensile properties of cold worked René 41. Both smooth and notched specimens exposed under stress at 650°, 800°, 1000° and 1200°F exhibited room temperature properties very similar to the unexposed alloy. The apparent lowering of tensile properties in the case of the longitudinal notched specimens was probably the result of material variability rather than any influence of stressed exposure.

The results of a limited study designed to determine the influence of plastic strain introduced prior to stressed exposure on tensile properties are listed in Table VIII. After the specimens were strained between 0 and 3 percent at 1000°F they were exposed for 1000 hours at 1000°F under stresses from 40 to 80 ksi. Upon completion of the stressed exposure the specimens were tensile tested at either room temperature or 1000°F. The results of this study are shown in Figure 8. In this graph the ultimate tensile strength of the material is plotted as a function of the amount of plastic strain introduced prior to exposure. The ultimate tensile strength is shown to increase markedly with the amount of prior plastic strain.

While it is not possible to completely separate the effects due to plastic strain from any which might result from varying exposure stress, it is highly likely that the plastic strain and not the exposure stress caused the pronounced increase in tensile strength. Figure 7 shows that the amount of creep caused by a stress of 80 ksi at 1000°F for 1000 hours would be negligible. Furthermore, the data presented in Table VII showed stressed exposure to have very little influence on room temperature tensile properties.

The most satisfactory explanation for the increase in ultimate tensile strength as a function of plastic strain is the occurrence of a strain-induced secondary precipitation. The amount of such a precipitate should increase with increasing strain. This in turn would be related to the degree of increase in tensile strength.

A strain-induced precipitation would not only account for the smooth specimen results shown in Figure 8 but would also help explain the notched specimen results. At 800°F the notched specimens withstood exposure without rupturing for times up to 2000 hours at stresses of 99 percent of the notch strength of the material. At 1000° and 1200°F, however, the notched specimens failed in relatively short times at stresses as low as 30 percent of the notched specimen tensile strength. This suggests that creep is necessary before failure can occur. If the creep which takes place in this alloy at 1000° and 1200°F causes a strain-induced precipitate to form then the precipitate could strengthen and coincidentally embrittle the alloy. The ductilities of the tensile specimens plastically strained prior to stressed exposure (Table VIII) are significantly lower than those which were not strained.

Since very little creep occurs at 800°F even at very high stresses, the amount of the strain-induced precipitate formed would be very limited. This may well be the reason why the embrittlement did not take place at this temperature.

As previously mentioned, anisotropy effects in the cold worked sheet material should also limit rupture ductility in certain specimen orientations. The combination of the strain-induced precipitate and specimen anisotropy should account for the low notched specimen results. The influence of the strain-induced precipitation should be more pronounced in notched specimens than in smooth specimens. This would result from the presence of the stress concentration which would effectively segregate most of the strain to the area of the root of the notch. The strain-induced precipitation would tend to embrittle the material at the root of the notch and thereby limit the notched specimen rupture life of the alloy.

Waspaloy

This alloy, like the René 41, was studied in two conditions of treatment, the annealed and aged condition and the cold reduced 40 percent and aged condition.

Annealed and Aged Condition. - Smooth specimen results are reported in Table IX for creep-rupture tests at 800°, 1000° and 1200°F. The general behavior of the smooth specimens was very similar to that exhibited by the René 41 alloy. Specimens exposed at 800°F under stresses as high as 98 percent of the notched specimen tensile strength did not fail in times up to 1200 hours. At 1000°F the stress-rupture time curve (Figure 9) was relatively flat and evidenced little influence of specimen orientation. At 1200°F the specimens tended to fail under the collars and at the pinholes. For this reason a reliable stress-rupture time curve could not be established at this temperature.

The notched specimens (results reported in Table X) also behaved in a manner similar to the annealed and aged René 41 notched specimens. None of the notched specimens fractured in 1000 hours at 800°F except one which broke on initial loading. In the shorter time periods at 1000°F the notched specimen stress-rupture time curve was relatively flat. The curve thereafter, however exhibited a rather sharp break downward at approximately 600 hours (Figure 10). At 1200°F the results showed a significant amount of scatter. At this temperature insufficient numbers of tests were run to establish the limits of the scatter band of the notched results.

Figure 11 shows the minimum creep rates exhibited by the alloy as a function of stress. There does not appear to be any influence of specimen orientation on the creep rate. This conclusion, however, is based on limited data.

The results of a study of the influence of elevated temperature stressed exposure on the room temperature tensile properties of annealed and aged Waspaloy are presented in Table XI. These results, as did those for René 41, show no significant influence of stressed exposure on subsequent room temperature tensile properties.

Cold Reduced and Aged Condition. - The minimum creep rates and stress-rupture time data obtained from tests on smooth specimens at temperatures from 800° to 1200°F are tabulated in Table XII. The tests at 800°F did not rupture in times from 1000 to 1400 hours at stresses which were as high as the reported ultimate strength of the alloy in the same condition (Ref. 1). Figure 12 shows the stress-rupture time curves obtained from the smooth specimens at 1000° and 1200°F. At both temperatures the specimens tended to fracture underneath the clamp-on collars used to hold the extensometer bars. A number of tests were carried out in which the testing conditions were duplicated, except that collars were not attached to the specimens. The results were rather startling in that no definite evidence was found to indicate that the collars had any influence on rupture life. There were just as many cases where specimens tested in the presence of collars ruptured in longer times than specimens without collars tested under identical conditions as there were cases where the reverse was true. The conclusion has to be reached that the influence of the collars on rupture life was minor compared with the inherent variability of the cold worked Waspaloy sheet material, even though rupture occurred where the collars were attached to the specimens.

At 1000°F the stress-rupture properties of smooth specimens taken in the transverse direction were poorer than the properties exhibited by longitudinal specimens (Figure 12). This behavior was not evident at 1200°F. The inferior properties at 1000°F of the transverse specimens were probably due to anisotropy effects on rupture ductility. Why this same behavior did not occur at 1200°F is not known.

The results of the notched specimen tests at 1000° and 1200°F are reported in Table XIII. Examination of these data, which are graphically presented in Figure 13, shows that the transverse notched specimen properties were inferior to the properties of the longitudinal specimens. This was true at both 1000° and 1200°F and was probably due to anisotropy effects. While some scatter of the notched specimen properties existed, it was significantly less than was noted for the René 41 sheet material.

The creep data obtained from the smooth specimens are plotted in Figure 14. No difference in minimum creep rate data with specimen orientation was observed. The curve drawn through the 1200°F results had a greater slope than the curves drawn through the data obtained from the tests at 800° or 1000°F, which were parallel to one another.

Stressed exposure at temperatures from 650° to 1200°F had very little influence on the room temperature tensile strength of either notched or smooth specimens. These data are reported in Table XIV. The only exception to this statement might be the longitudinal notched specimen exposed for 2800 hours at 1200°F under 40,000 psi stress. The notch strength of this specimen at room temperature was only 150,000 psi compared with 212,000 psi for the unexposed alloy. A transverse specimen exposed at 1200°F, however, did not show any reduction in notch strength compared with the unexposed material.

Table XV lists the results of a limited study of the influence of plastic strain on tensile properties. As was the case with the cold worked René 41, plastic strain introduced prior to stressed exposure for 1000 hours at 1000°F caused the ultimate tensile strength of the material to be increased at both room temperature and 1000°F. These results are shown in Figure 15. As was noted previously for the René 41 results, the increase in tensile strength was probably due to a strain-induced precipitation. An interesting feature of these tests as well as the tests on the cold reduced René 41 was that it was necessary in several cases to exceed the reported ultimate strength of the material in order to introduce the desired amount of plastic strain into the specimens. In these cases the stress applied to the specimens was as much as 5 percent greater than the tensile strength of the alloys. This again indicates that the straining acted to strengthen the alloys through a mechanism involving the formation of a strain-induced precipitate.

A limited number of rupture tests was conducted at 1200°F under 100,000 psi on specimens containing notches of varying sharpness. The results of these tests are reported in Table XVI. These results show that the rupture life falls off very rapidly with increasing notch acuity. On the average specimens with dull notches having a $K_t = 1.5$ showed a marked drop in rupture time compared with smooth specimens. When the theoretical elastic stress concentration factor of the notched specimens exceeded 3 the rupture properties of the alloy were approximately as poor as observed in the presence of sharp notches having a K_t in excess of 20. These results were surprising since these types of alloys usually exhibit notch strengthening at low values of notch acuity (Ref. 4).

Applicability of Results

In the application of the results to the determination of the upper temperature of usefulness of René 41 and Waspaloy in the supersonic transport several reference parameters were used. These reference parameters were as follows:

1. Stress for rupture in 50,000 hours.

2. Stress to produce a minimum creep rate of 0.1 percent in 50,000 hours.

3. Minimum time for rupture of specimens containing the ASTM sharp edge-notch at a stress of 40,000 psi.

These reference parameters were selected on the basis of simplified design requirements for the supersonic transport. In the SST application the design stress for the superalloys is expected to be 40,000 psi. The alloys must be able to withstand this stress for an operating life of 50,000 hours without failing and without accumulating more than 0.1 percent creep.

In theory the ASTM sharp edge-notch simulates a crack. The superalloys must be able to withstand the presence of cracks under the design stress for prolonged periods of time at the upper use temperature.

From the preceding considerations the three above-listed reference parameters were selected. For a material to be serviceable at the upper temperature it would have to have a stress for rupture in 50,000 hours of at least 40,000 psi if rupture strength limits the upper use temperature. If the controlling function is creep resistance then the upper temperature of usefulness would be that temperature where a stress of 40,000 psi causes an accumulation of approximately 0.1 percent in 50,000 hours. A minimum creep rate of 0.000001 percent per hour should approximate a total accumulation of about 0.1 percent plastic strain in 50,000 hours. This approximation has been made in order to allow for any primary creep which might occur in the structure. Finally, if the factor which controls the peak temperature is the resistance of the material to the presence of cracks then the alloys should be able to withstand these cracks for prolonged time periods under a stress of 40,000 psi. The length of these prolonged periods has not been determined, however, they should be sufficiently long to allow for the detection of cracks. For the purpose of this report this time period has been arbitrarily selected as 10,000 hours.

Stress for Rupture in 50,000 Hours. - Linear extrapolations of the log stress-log rupture time curves (Figures 2, 5, 9, 12) were made to arrive at the stress for rupture in 50,000 hours for smooth specimens of both alloys in each condition of prior treatment and in each orientation. These results are presented in Table XVII. Extrapolations of the data obtained from both alloys in the annealed and aged conditions at 1200°F could not be justified because of the scatter of the results and the lack of long-time data.

Examination of the data shown in Table XVII shows that both alloys in the cold worked condition are suitable for service up to at least 1200°F from the standpoint of rupture strength. The cold reduced René 41 gave appreciably higher rupture strength than did the Waspaloy. Both alloys in their annealed and aged conditions exhibited strengths which would ensure more than adequate rupture life at temperatures of at least 1000°F. It is likely that the alloys in the annealed and aged condition could be used at temperatures somewhat above 1000°F.

Creep Resistance. - In Table XVIII the stresses to produce a minimum creep rate of 0.000001 percent per hour at 800°, 1000° and 1200°F have been tabulated. This minimum creep rate together with the deformation on loading and primary creep should correspond to an approximate accumulation of 0.1 percent plastic strain in 50,000 hours. The data presented in Table XVIII were obtained by linear extrapolations of the log stress-log minimum creep rate curves of Figures 4, 7, 11 and 14.

Examination of the data shows that both alloys in both conditions of prior treatment exhibit stresses to produce a minimum creep rate of 0.000001 percent per hour greater than 40,000 psi at temperatures of up to and including 1200°F. Based on this reference parameter the alloys in the conditions in which they were tested in this program are suitable for service in the supersonic transport at temperatures of up to at least 1200°F.

Notch Resistance. - Due to the wide scatter of the results obtained from the specimens containing the ASTM sharp edge-notch it was impossible in some cases to extrapolate the data to determine the time for rupture of these specimens under a stress of 40,000 psi. Estimates of the minimum time for rupture of the notched specimens under this stress, however, have been made. These estimates were based on the observed width of the scatter band of the data and on the maximum observed slope of the log stress-log rupture time curves. These estimated times are tabulated in Table XIX. If these estimates are approximately correct then neither the René 41 nor the Waspaloy in the conditions in which they were tested in this investigation is suitable for service in the supersonic transport at 1000°F or above.

The results obtained from the alloys at 800°F, however, indicate satisfactory properties at this temperature. At this temperature only two specimens which survived initial loading fractured during exposure in times up to 2000 hours. These two specimens were loaded to stress levels well above 100,000 psi.

Although the reference parameters of rupture strength, creep resistance and notch resistance in tensile tests before and after exposure indicate adequate properties for the SST, the upper temperature of usefulness of the materials tested was limited to between 800° and 1000°F by sensitivity to cracks and stress concentrations under creep conditions. Since materials operating in the area of the engines of the SST will be required to withstand temperatures up to approximately 1200°F for prolonged periods of time, the materials tested would be unsatisfactory for application at higher temperatures.

Additional research should be carried out to determine if this sensitivity to notches under creep conditions is typical of the René 41 and Waspaloy alloys. This research should include a study of the effects of other heat treatments. In particular it should be established whether or not the notch sensitivity could be eliminated by heat treatments leading to lower strength levels in the alloys.

Certainly the research should look for alloys which will not be subject to this weakness. The other materials proposed for the SST, titanium alloys and precipitation hardened stainless steels, probably would not maintain sufficient creep resistance for application at these temperatures. If the results obtained in this investigation are typical of René 41 or Waspaloy it will be necessary to find alloys and/or heat treatments which will have or give satisfactory strength levels with suitable notched specimen strength and stability during and after exposure.

CONCLUSIONS

An investigation of the tensile, creep and rupture properties of René 41 and Waspaloy sheet materials at temperatures from 800° to 1200°F has been carried out. Both alloys were tested in the annealed and aged condition as well as in the cold reduced and aged condition. The cold working of these alloys resulted in much higher strengths than could have been obtained by heat treatment alone. From the results of this study the following conclusions can be drawn:

1. In the conditions in which these alloys were tested their upper temperature of usefulness in the proposed supersonic transport is limited by the poor resistance of the alloys to the presence of cracks and stress concentrations when they are exposed to temperatures where significant amounts of creep can occur. In this investigation cracks were simulated in specimens by ASTM sharp edge-notches.

2. The creep resistance and rupture strength of both alloys in the cold worked and aged condition were above the expected design stress of 40,000 psi at temperatures up to 1200°F.

3. The creep resistance as measured by the stress required to produce a minimum creep rate of 0.000001%/hour of both René 41 and Waspaloy in their annealed and aged conditions was in excess of 40,000 psi at temperatures up to 1200°F.

4. The stress required for rupture in 50,000 hours of the alloys in the annealed and aged condition was in excess of 100,000 psi at 1000°F.

5. The resistance of the alloys during stressed exposure in both conditions of prior treatment to sharp edge-notches and stress concentrations was satisfactory at 800°F but not at 1000°F or 1200°F.

6. Tests at 1200°F on specimens of Waspaloy in the cold worked and aged condition showed that mild notches (K_t = 3.1 or above) were as detrimental to the properties of the alloy as sharp edge-notches ($K_t > 20$).

   Specimens containing notches with theoretical elastic stress concentration factors of 1.5 and 2.1 had stress-rupture time properties at 1200°F much poorer than exhibited by smooth specimens.

7. With very few exceptions stressed exposure for time periods up to 4000 hours at temperatures from 650° to 1200°F had no effect on the subsequent room temperature tensile properties of either the Waspaloy or the René 41 sheet materials.

8. If the use of superalloys in certain sections of the SST requires that these materials withstand prolonged exposure to temperatures of 1000°F or above, then René 41 and Waspaloy of the quality and/or in the conditions of prior treatment in which they were tested in this investigation are not suitable for the application.

The conclusions expressed are only intended to apply to René 41 and Waspaloy in the conditions in which they were tested in this investigation. There may well be conditions of melting, processing and/or heat treatment which when applied to these alloys would ensure their satisfactory performance in the supersonic transport. Conversely, the stress-rupture time characteristics of other alloys being considered for use in the SST have not to the authors' knowledge been evaluated with specimens containing cracks or sharp edge-notches, the conditions shown in this investigation to limit the usefulness of René 41 and Waspaloy to temperatures below 1000°F. It is possible that these alloys may also exhibit a sensitivity to the presence of notches and stress concentrations when exposed for prolonged time periods under creep conditions.

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TABLE I

Chemical Compositions of Experimental Materials

Alloy	Heat Number	C	Si	Mn	Cr	Ni	Co	Mo	Ti	Al	Fe	S	B	Zr
Rene'41	R-217	.09	.07	.06	18.97	Bal.	11.20	9.75	3.20	1.50	<.30	.006	.0045	-
Rene'41	R-216	.10	.06	.06	18.48	Bal.	10.43	9.37	3.19	1.42	2.20	.007	.0047	-
Waspaloy	B-119	.08	.07	.04	19.63	Bal.	13.49	4.26	2.99	1.40	2.30	.007	.0048	.03

TABLE II

Summary of test results from smooth specimens of Rene' 41 - annealed at 1975°F, W.Q., and aged for 16 hours at 1400°F

Specimen Code	Direction-ality	Temp. (°F)	Stress (Ksi)	Rupture Life (hrs)	Elong. (%)	Minimum Creep Rate (%/hr)
RLS144	Long.	800	175	>2000[a]		0.000063
RTS120	Trans.	800	180	>1000[b]		0.000116
RLS140	Long.	1000	170	56.3	20.8	0.0118
RLS23	"	"	165	283.4	11.5	
RLS141	"	"	160	648.2		0.00062
RTS117	Trans.	1000	170	69.0	10.2	0.0104
RTS113	"	"	165	163.1	12.5	
RTS112	"	"	165	193.7	10.7	
RTS111	"	"	150	601.8[c]	5.2	0.00024
RTS116	"	"	150	645.4	6.5	0.00034
RTS110	"	"	130	>1000[b]	0.8	0.0000134
RTS114	Trans.	1200	165	0[d]	11.0	
RTS115	"	"	145	1.9	2.7	
RTS118	"	"	135	10.0[e]	3.0	0.053
RTS119	"	"	125	42.6[c]	1.25	0.0095
RTS122	"	"	125	20.9[c]		
RLS143	Long.	1200	140	14.9[e]	1.5	

a - Interrupted after 2000 hours

b - Interrupted after 1000 hours

c - Broke at Pin Hole

d - Broke on loading

e - Fractured under Collar

TABLE III

Summary of test results from notched specimens of Rene' 41 - annealed at 1975°F, W.Q., and aged for 16 hours at 1400°F

Specimen Code	Directionality	Temperature (°F)	Stress, ksi	Rupture Time (hrs)
RLN137	Longitudinal	800	145	>1000[a]
RLN160	"	"	140	>1000[a]
RTN108	Transverse	800	145	>1000[a]
RTN107	"	"	135	>1000[a]
RLN133	Longitudinal	1000	120	315.3
RLN134	"	"	110	149.0
RLN26	"	"	100	446.9
RLN27	"	"	80	788.0
RLN28	"	"	60	2903.0
RTN101	Transverse	1000	120	71.0
RTN102	"	"	110	230.6
RTN19	"	"	100	447.3
RTN16	"	"	80	856.3
RTN15	"	"	60	1831.5
RLN130	Longitudinal	1200	100	20.0
RLN131	"	"	80	73.7
RLN135	"	"	70	32.4
RLN138	"	"	65	21.3
RLN132	"	"	60	149.4
RLN139	"	"	55	23.0
RTN104	Transverse	1200	100	20.0
RTN105	"	"	80	14.8
RTN103	"	"	80	12.4
RTN106	"	"	70	24.9
RTN100	"	"	60	>2000[b]

a - Interrupted after 1000 hours

b - Interrupted after 2000 hours

TABLE IV

Tensile Properties at Room Temperature of Interrupted Specimens of Rene' 41 in the Annealed and Aged Condition

Exposure Conditions			Tensile Properties		
Temp. °F	Time hrs.	Stress ksi	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elong. %
Longitudinal Smooth Specimens					
None			204	154	22
650	1000	40	196	155	16
800	1000	40	187	156	11
1000	1000	40	203	157	24
1200	1000	40	213	167	22
Transverse Smooth Specimens					
None			204	154	23
650	1000	40	195	152	13
800	1000	40	201	154	25
1000	1000	40	201	-	19
1000	1000	130	204	174	13
1200	1000	40	206	161	19
Longitudinal Notched Specimens					
None			172		
650	1000	40	170		
800	1000	40	169		
800	1000	145	158		
1000	1000	40	166		
1000	1000	40	176[a]		
1200	1000	40	170		
Transverse Notched Specimens					
None			171		
650	1000	40	162		
800	1000	40	169		
800	1000	135	164		
800	1000	145	161		
1000	1000	40	159		
1000	1000	40	169[a]		
1200	1000	40	148		
1200	2000	60	137		

a - Notch machined after exposure

TABLE V

Summary of test results from smooth specimens of Rene' 41 - Cold Worked 35 percent and aged for 2 hours at 1500°F

Specimen Code	Direction-ality	Temp. °F	Stress ksi	Rupture Life Hours	Elong. %	Minimum Creep Rate %/hr.
R2LS53	Long.	800	218	>2000[a]		0.00013
R2LS28	"	"	215	>1000[b]		0.00005
R2TS51	Trans.	800	210	>1400[c]		0.00008
R2TS48	"	"	205	>1000[b]		0.00004
R2LS50	Long.	1000	215	0[d]	5.3	
R2LS48	"	"	210	240.0	3.0	0.0151
R2LS43	"	"	210			0.00863
R2LS42	"	"	200	485.7	4.5	0.00575
R2LS51	"	"	195	599.2[e]	4.5	0.00295
R2LS40	"	"	185	1951.3[e]	3.5	0.00095
R2LS43	"	"	150			0.00008
R2TS37	Trans.	1000	200	81.1	2.5	0.0136
R2TS33	"	"	200			0.0071
R2TS42	"	"	190	156.0[e]	1.5	0.00414
R2TS39	"	"	180	240.5[e]	1.0	0.00079
R2TS32	"	"	165	451.9[e]	1.0	0.000176
R2TS40	"	"	150	>4000[f]		0.000032
R2TS33	"	"	150			0.00005
R2LS44	Long.	1200	200	0.5	18.5	10.0
R2LS45	"	"	185	1.1	18.2	5.0
R2LS52	"	"	150	31.1	11.5	
R2LS46	"	"	130	129.3	4.5	0.0152
R2LS41	"	"	115	389.1	9.5	0.00556
R2LS49	"	"	105	924.7	10.3	0.00181
R2TS35	Trans.	1200	185	1.4[e]	4.5	2.0
R2TS34	"	"	165	2.5[e]	2.0	0.40
R2TS43	"	"	150	8.8	2.0	0.0240
R2TS36	"	"	130	74.8	2.5	0.00390
R2TS39	"	"	115	372.4	4.5	0.00172
R2TS41	"	"	105	672.1[e]	1.5	

a - Interrupted after 2000 hours
b - Interrupted after 1000 hours
c - Interrupted after 1400 hours
d - Broke on loading
e - Fractured under collar
f - Interrupted after 4000 hours

TABLE VI

Summary of test results from notched specimens of Rene' 41 - Cold Worked 35 percent and aged for 2 hours at 1500°F

Specimen Code	Orientation	Temp. °F	Stress, ksi	Rupture Life Hours
R2LN67	Long.	800	140	>1000[a]
R2LN69	"	"	130	>1200[b]
R2TN111	Trans.	800	145	0[c]
R2TN113	"	"	140	0[c]
R2TN114	"	"	135	890.7
R2TN115	"	"	130	>1200[b]
R2LN58	Long.	1000	115	37.8
R2LN43	"	"	115	79.5
R2LN59	"	"	100	237.3
R2LN41	"	"	100	143.6
R2LN64	"	"	90	37.5
R2LN57	"	"	90	294.8
R2LN60	"	"	80	2369.2
R2LN40	"	"	80	442.2
R2LN61	"	"	75	>2000[d]
R2LN63	"	"	70	>2400[e]
R2LN39	"	"	60	>3000[f]
R2TN37	Trans.	1000	115	24.3
R2TN32	"	"	100	53.8
R2TN34	"	"	100	105.4
R2TN101	"	"	90	66.3
R2TN105	"	"	90	190.4
R2TN102	"	"	80	144.8
R2TN33	"	"	80	188.9
R2TN103	"	"	70	514.8
R2TN107	"	"	70	192.2
R2TN112	"	"	65	691.0
R2TN38	"	"	60	>3342.4[g]
R2TN12	"	"	40	743.3
R2TN17	"	"	40	941.9
R2TN13	"	"	40	>1000[a]
R2TN16	"	"	40	>1000[a]
R2TN18	"	"	40	>1000[a]

continued ....

TABLE VI concluded

Summary of test results from notched specimens of Rene 41 - Cold Worked 35 percent and aged for 2 hours at 1500°F

Specimen Code	Orientation	Temp. °F	Stress, ksi	Rupture Life Hours
R2LN66	Long.	1200	100	6.4
R2LN62	"	"	90	2.9
R2LN42	"	"	80	881.9
R2LN65	"	"	60	>2000[d]
R2TN110	Trans.	1200	80	1.4
R2TN104	"	"	70	6.3
R2TN109	"	"	60	83.8
R2TN108	"	"	50	211.9
R2TN106	"	"	45	>2000[d]

a - Discontinued after 1000 hours
b - Discontinued after 1200 hours
c - Broke on loading
d - Discontinued after 2000 hours
e - Discontinued after 2400 hours
f - Discontinued after 3000 hours
g - Discontinued after 3342 hours

TABLE VII

Tensile Properties at Room Temperature of Interrupted Specimens of Rene' 41 in the Cold Reduced and Aged Condition

Exposure Conditions			Tensile Properties		
Temp. °F	Time hrs.	Stress ksi	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elong. %
Longitudinal Smooth Specimens					
None			249	230	8
650	1000	40	246	230	9
800	1000	215	271[a]		2
1000	1000	40	251	237	7
Transverse Smooth Specimens					
None			237	216	7
650	1000	40	242	222	7
800	1000	205	246		5
800	1000	210	268[a]		1.5
1000	1000	40	240	221	6
1000	4000	150	271	261	2
Longitudinal Notched Specimens					
None			196		
650	1000	40	182		
800	1000	140	173		
1000	1000	40	147		
1000	3000	60	156		
1000	2400	70	164		
1000	2000	75	180		
1200	2000	60	164		
Transverse Notched Specimens					
None			182		
650	1000	40	190		
1000	1000	40	161		
1200	2000	45	120		

a - Specimen fractured under collar

TABLE VIII

Influence of Plastic Strain and Stressed Exposure at 1000°F for 1000 hours on the Tensile Strength of Rene' 41 - Cold Worked 35 percent and aged for 2 hours at 1500°F

Specimen Code	Directionality	Exposure Stress, ksi	Plastic Strain, %	Max. Applied Stress psi	Temp. of Tensile Test °F	Ultimate Tensile Strength ksi	0.2% Offset Yield Strength, ksi	Elongation %
R2LS[a]	Long.	0	0		R.T.	249	230	8.0
R2LS	"	40	0		"	251	237	7.0
R2LS38	"	60	1.0	210,914	"	275	272	1.5
R2LS39	"	80	2.0	229,537	"	289	-[b]	1.5
R2TS[a]	Trans.	0	0		R.T.	237	216	7.0
R2TS	"	40	0		"	240	221	6.0
R2TS19	"	60	1.2	206,879	"	260	-[b]	3.0
R2TS18	"	80	2.2	229,787	"	265	265	1.0
R2LS[a]	Long.	0	0		1000	221	201	3.8
R2LS	"	40	0		"	227	206	3.0
R2LS36	"	60	2.7	208,160	"	239.5	234	1.5
R2LS35	"	80	1.2	224,194	"	231	-[b]	1.0
R2TS[a]	Trans.	0	0		1000	218	194	5.0
R2TS	"	40	0		"	219	193	3.5
R2TS30	"	60	2.0	214,678	"	230.5	228	2.5
R2TS20	"	80	2.0	210,914	"	233	219	1.2

a - specimen not exposed b - yield strength determination could not be made

TABLE IX

Summary of test results from smooth specimens of Waspaloy - annealed and aged for 16 hours at 1400°F

Specimen Code	Direction-ality	Temp. °F	Stress ksi	Rupture Time (hrs)	Elong %	Minimum Creep Rate %/hr.
WLS117	Long.	800	155	>1200[a]		0.0005
WTS133	Trans.	800	160	>1000[b]		0.00008
WLS9	Long.	1000	145	157.3	11.0	0.00357
WLS111	"	"	135	420.7	7.3	0.0007
WLS115	"	"	135	577.4	7.0	0.00061
WLS10	"	"	125	2592.4	4.0	0.0000216
WLS110	"	"	105	>1000[b]	0.3	(c)
WTS17	Trans.	1000	150	227.4	8.5	
WTS10	"	"	145	181.3	12.0	0.0042
WTS134	"	"	135	>2000		0.00002
WTS9	"	"	125	2916.8		0.0000345
WLS112	Long.	1200	140	1.4[d]	3.9	
WLS113	"	"	120	14.5	2.0	0.06
WLS114	"	"	100	127[e]	0.5	0.0017
WLS116	"	"	100	40.1[d]	1.5	0.00213
WLS118	"	"	100	40.1[e]		
WTS18	Trans.	1200	140	1.4	6.5	
WTS19	"	"	120	19.5[d]	2.0	

a - Interrupted after 1200 hours

b - Interrupted after 1000 hours

c - No measurable creep

d - Fractured under Collar

e - Broke at pin hole

TABLE X

Summary of test results from notched specimens of Waspaloy - annealed and aged for 16 hours at 1400°F

Specimen Code	Direction-ality	Temp. °F	Stress, ksi	Rupture Time hours
WLN108	Long.	800	135	0[a]
WLN106	"	"	130	>1000[b]
WLN105	"	"	125	>1000[b]
WTN129	Trans.	800	135	>1000[b]
WTN131	"	"	130	>1200[c]
WTN128	"	"	125	>1000
WLN101	Long.	1000	115	0[a]
WLN14	"	"	100	895.1
WLN102	"	"	80	1039.0
WLN13	"	"	60	2637.0
WTN124	Trans.	1000	115	301.3
WTN16	"	"	100	383.6
WTN125	"	"	80	>2000[d]
WTN14	"	"	60	2128.2
WLN100	Long	1200	80	22.4
WLN103	"	"	60	149.4
WLN107	"	"	55	19.5
WLN104	"	"	50	980.3
WTN123	Trans.	1200	80	21.4
WTN126	"	"	60	117.7
WTN130	"	"	55	28.6
WTN127	"	"	50	883.9

a - Broke on loading

b - Interrupted after 1000 hours

c - Interrupted after 1200 hours

d - Interrupted after 2000 hours, specimen cracked through about 20 percent of its area.

TABLE XI

Tensile Properties at Room Temperature of Interrupted Specimens of Waspaloy in the Annealed and Aged Condition

Exposure Conditions			Tensile Properties		
Temp. °F	Time hours	Stress ksi	Ultimate Strength, ksi	0.2% Offset Yield Strength ksi	Elong. %
Longitudinal Smooth Specimens					
None			191	139	31
650	1000	40	186	135	31
1000	1000	40	192	144	31
1000	1000	105	200	149	25
Transverse Smooth Specimens					
None			190	135	31
650	1000	40	184	132	31
1000	1000	40	187	137	30
Longitudinal Notched Specimens					
None			154		
650	1000	40	161		
800	1000	125	157		
800	1000	130	155		
1000	1000	40	159		
Transverse Notched Specimens					
None			151		
650	1000	40	163		
800	1000	125	156		
800 •	1000	135	159		
1000	1000	40	159		

TABLE XII

Summary of test results from smooth specimens of Waspaloy - Cold worked 40 percent and aged for 2 hours at 1500°F

Specimen Code	Directionality	Temp. °F	Stress ksi	Rupture Life hours	Elong. %	Minimum Creep Rate %/hr.
W3LS103	Long.	800	204	>1000[a]		0.00012
W3LS47	"	"	200	>1400[b]		0.00011
W3TS40	Trans.	800	197	>1300[c]		0.000086
W3TS37	"	"	195	>1000[a]		0.000063
W3LS25	Long.	1000	195	43.2	9.5	0.1
W3LS31	"	"	195	-	-	0.0204
W3LS45	"	"	185	131.7[d]	3.5	
W3LS41	"	"	180	252.5	3.5	0.0093
W3LS28	"	"	165	57.5[d]	1.0	0.005
W3LS33	"	"	165	968.0	1.7	0.00111
W3LS46	"	"	160	727.4[d]	1.7	0.0001055
W3LS32	"	"	150	1301.4[d]	1.8	0.0005
W3TS24	Trans.	1000	190	-	-	0.0204
W3TS18	"	"	190	17.3	5.5	0.138
W3TS35	"	"	170	104.6	2.5	0.0074
W3TS21	"	"	165	266.2	1.5	0.00091
W3TS29	"	"	150	927.2[d]	1.0	0.000132
W3LS34	Long.	1200	140	11.4[d]	4.0	0.305
W3LS42	"	"	140	8.8[e]	4.0[g]	
W3LS35	"	"	120	32.7[d]	2.0	0.0357
W3LS43	"	"	120	72.1[e]	3.3	
W3LS36	"	"	100	79.4[d]	0.5	0.0021
W3LS44	"	"	100	394.6[e]	2.5	
W3LS40	"	"	90	954.6[d]	2.0	0.0009
W3LS39	"	"	75	>1700[f]		0.000135
W3TS30	Trans.	1200	140	8.9	2.5	0.21
W3TS31	"	"	120	79.7[d]	2.0	0.0125
W3TS33	"	"	120	33.8[e]	2.5	
W3TS32	"	"	100	378.3[d]	1.5	0.00133
W3TS34	"	"	100	276.0[e]	1.5	
W3TS102	"	"	90	345.2[d]	1.0	0.000715
W3TS36	"	"	90	554.1[e]	1.5[g]	
W3TS20	"	"	75	1117.2[d]	2.3	0.000192

a - Interrupted after 1000 hours
b - Interrupted after 1400 hours
c - Interrupted after 1300 hours
d - Fractured under collar
e - Test run without collars
f - Interrupted after 1700 hours
g - Fractured at fillet

TABLE XIII

Summary of test results from notched specimens of Waspaloy - Cold worked 40 percent and aged for 2 hours at 1500°F

Specimen Code	Directionality	Temperature °F	Stress, ksi	Rupture Life hours
W3LN120	Long.	800	155	0[a]
W3LN50	"	"	155	>1200[b]
W3LN49	"	"	150	>1000[c]
W3LN119	"	"	140	>1000[c]
W3TN61	Trans.	800	160	0[a]
W3TN43	"	"	155	>1000[c]
W3TN62	"	"	150	0[a]
W3TN42	"	"	140	752.0
W3LN33	Long.	1000	100	134.9
W3LN126	"	"	90	150.5
W3LN38	"	"	80	436.6
W2LN125	"	"	75	481.7
W3LN118	"	"	70	448.2
W3LN39	"	"	60	>3150[d]
W3TN34	Trans.	1000	100	14.1
W3TN50	"	"	80	40.6
W3TN41	"	"	70	173.7
W3TN49	"	"	60	101.6
W3TN40	"	"	55	103.6
W3TN36	"	"	50	>435.6[e]
W3LN36	Long.	1200	100	11.5
W3LN115	"	"	80	80.5
W3LN35	"	"	60	181.8
W3LN116	"	"	50	>3600[f]
W3LN117	"	"	40	>2800[g]
W3TN47	Trans.	1200	80	1.3
W3TN44	"	"	80	1.6
W3TN37	"	"	60	4.4
W3TN38	"	"	40	264.5
W3TN39	"	"	30	>2000[h]

a - Broke on loading
b - Interrupted after 1200 hours
c - Interrupted after 1000 hours
d - Interrupted after 3150 hours
e - Fuse blown, test discontinued
f - Interrupted after 3600 hours
g - Interrupted after 2800 hours
h - Interrupted after 2000 hours

TABLE XIV

Tensile Properties at Room Temperature of Interrupted Specimens of Waspaloy in the Cold Reduced and Aged Condition

Exposure Conditions			Tensile Properties		
Temp. °F	Time hours	Stress ksi	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elong. %
Longitudinal Smooth Specimens					
None			237	216	9
650	1000	40	227	206	10
800	1400	200	250[a]	244	2
800	1000	204	244	233	4
1000	1000	40	234	215	9
1200	1700	75	246	224	5
Transverse Smooth Specimens					
None			232	206	11
650	1000	40	224	201	9
800	1000	195	235		5
800	1300	197	237	237	4
1000	1000	40	228	208	9
Longitudinal Notched Specimens					
None			212		
650	1000	40	196		
800	1000	140	207		
800	1000	150	173		
1000	1000	40	193		
1000	3150	60	195		
1200	2800	40	150		
Transverse Notched Specimens					
None			201		
650	1000	40	196		
800	1000	155	179		
1000	1000	40	186		
1200	2000	30	186		

a - Specimen fractured under collar

TABLE XV

Influence of Plastic Strain and Stressed Exposure at 1000°F for 1000 hours on the Tensile Strength of Waspaloy - Cold Worked 40 percent and aged for 2 hours at 1500°F

Specimen Code	Directionality	Exposure Stress, ksi	Plastic Strain, %	Max. Applied Stress psi	Temp. of Tensile Test °F	Ultimate Tensile Strength ksi	0.2% Offset Yield Strength, ksi	Elongation, %
W3LS[a]	Long.	0	0		R.T.	237	216	9.0
W3LS	"	40	0		"	234	215	9.0
W3LS29	"	60	2.25	213,042	"	247	244	1.5
W3LS23	"	80	1.5	202,027	"	248	244	4.5
W3TS[a]	Trans.	0	0		R.T.	232	206	11.0
W3TS	"	40	0		"	228	208	9.0
W3TS19	"	60	1.0	186,852	"	233	230	8.0
W3TS25	"	60	1.75	198,259	"	240	240	4.0
W3TS26	"	60	2.0	189,994	"	242	242	5.5
W3TS23	"	80	1.25	185,892	"	232	225	4.2
W3LS[a]	Long.	0	0		1000	204	177	4.5
W3LS	"	40	0		"	213	190	3.5
W3LS26	"	60	1.25	201,000	"	216	205	2.0
W3LS24	"	80	2.5	205,220	"	223	-	1.7
W3LS22	"	100	1.7	202,408	"	224	218	2.25

a - Specimen not exposed

TABLE XVI

Influence of Notch Acuity on the Rupture Properties of Waspaloy in the Cold Worked and Aged Condition

Specimen Code	Notch Acuity K_t	Stress psi	Temperature °F	Rupture Time (hrs)
W3LS44	1.0	100,000	1200	394.6
W3LN64	1.5	"	"	130.4
W3LN63	1.5	"	"	404.2
W3LN59	2.1	"	"	26.9
W3LN58	2.1	"	"	141.0
W3LN60	3.1	"	"	20.7
W3LN61	3.1	"	"	16.4
W3LN56	5.9	"	"	10.9
W3LN57	5.9	"	"	5.2
W3LN54	9.4	"	"	12.0
W3LN55	9.4	"	"	1.4
W3LN36	>20	"	"	11.5

TABLE XVII

Stress for Rupture in 50,000 Hours

	1000°F	1200°F
Rene' 41		
cold reduced		
longitudinal	152,000 psi	77,000 psi
transverse	136,000 psi	77,000 psi
annealed		
longitudinal	144,000 psi	-
transverse	118,000 psi	-
Waspaloy		
cold reduced		
longitudinal	125,000 psi	52,000 psi
transverse	118,000 psi	52,000 psi
annealed		
longitudinal	110,000 psi	-
transverse	110,000 psi	-

TABLE XVIII

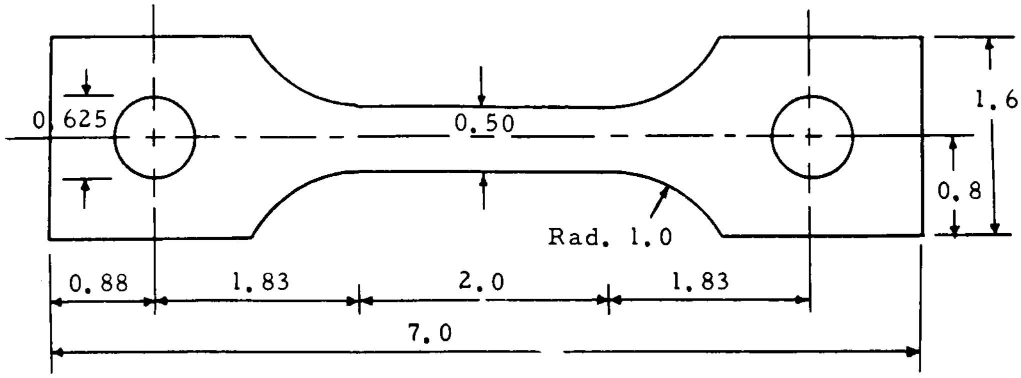
Stress for a Minimum Creep Rate of 0.000001%/hr.

	800°F	1000°F	1200°F
Rene' 41			
cold reduced	180,000 psi	118,000 psi	68,000 psi
annealed	150,000 psi	120,000 psi	68,000 psi
Waspaloy			
cold reduced	164,000 psi	124,000 psi	47,000 psi
annealed	-	112,000 psi	66,000 psi

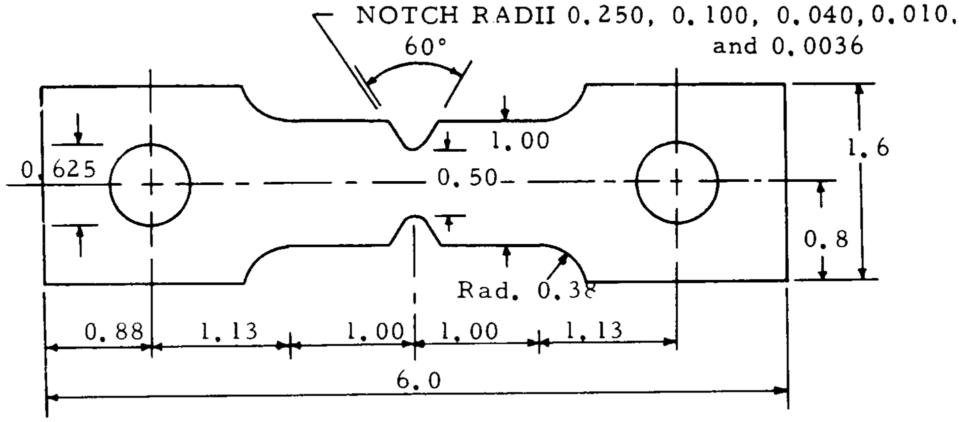
TABLE XIX

Estimated Minimum Time for Rupture of Notched Specimens under a Net Section Stress of 40,000 psi

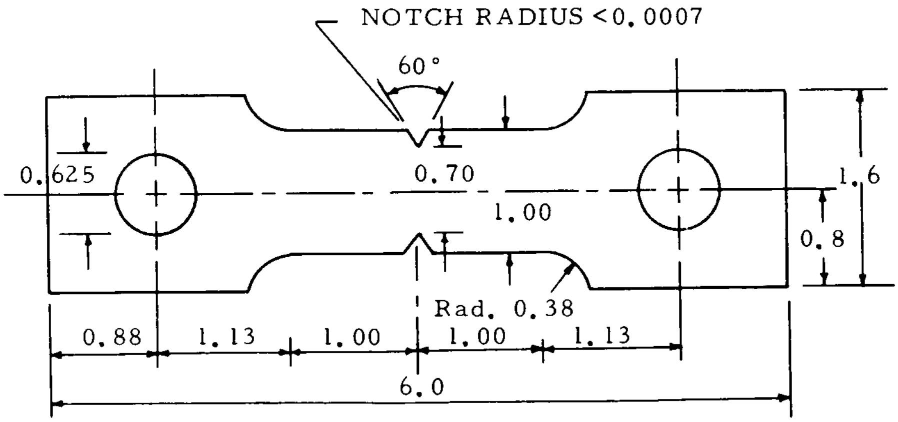
		1000°F	1200°F
Rene' 41			
cold reduced			
	longitudinal	12,000 hrs.	6000 hrs.
	transverse	700 hrs.	60 hrs.
annealed			
	longitudinal	5,500 hrs.	35 hrs.
	transverse	5,500 hrs.	28 hrs.
Waspaloy			
cold reduced			
	longitudinal	9,500 hrs.	4000 hrs.
	transverse	700 hrs.	100 hrs.
annealed			
	longitudinal	6,000 hrs.	120 hrs.
	transverse	6,000 hrs.	120 hrs.



1a. Smooth (unnotched specimen (K_t = 1.0).



1b. Notched specimen for K_t = 1.5, 2.1, 3.1, 8.6 and 9.4.



1c. ASTM sharp edge-notched specimen (K_t >20)

Figure 1. Types of Test Specimens (All dimensions in inches)

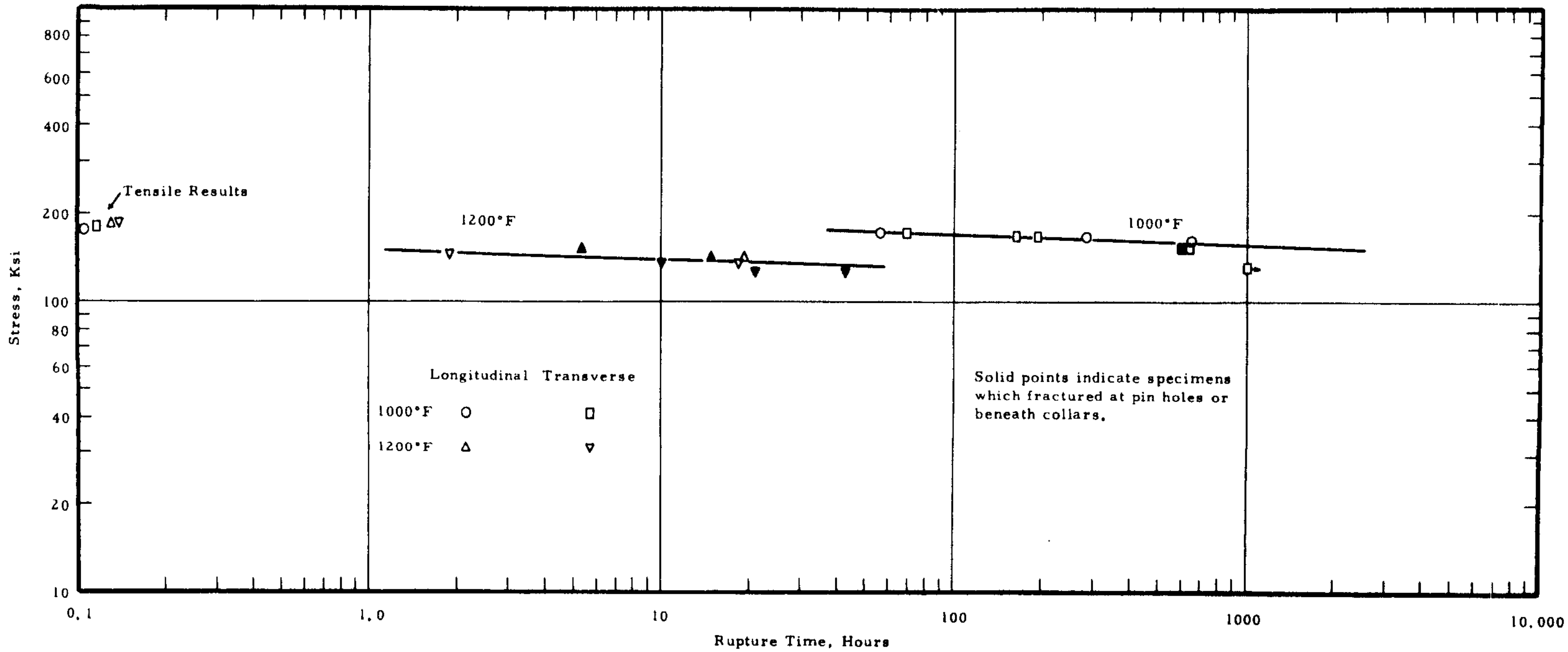


Figure 2. Stress versus rupture time data obtained from smooth specimens of Rene' 41 in the annealed and aged condition at 1000° and 1200°F.

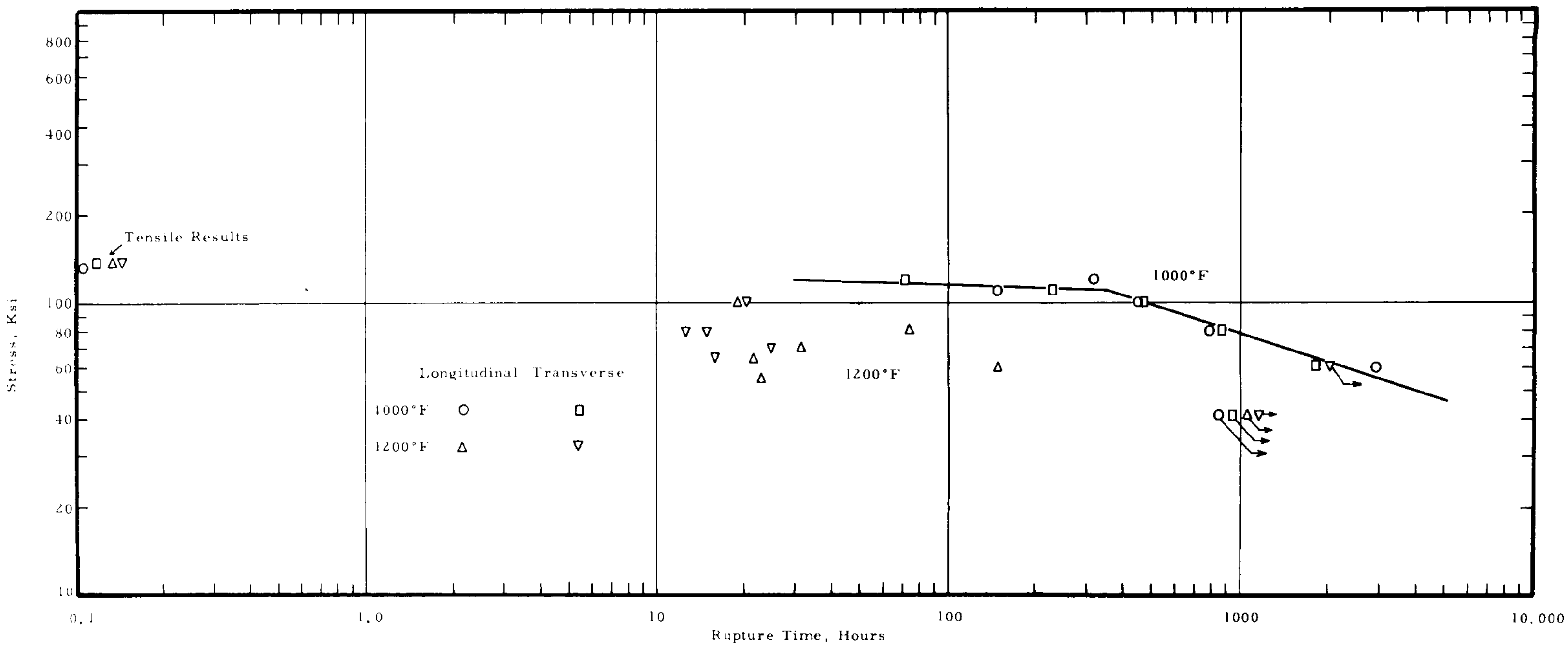


Figure 3. Stress versus rupture time data obtained from notched specimens of Rene' 41 in the annealed and aged condition at 1000° and 1200°F.

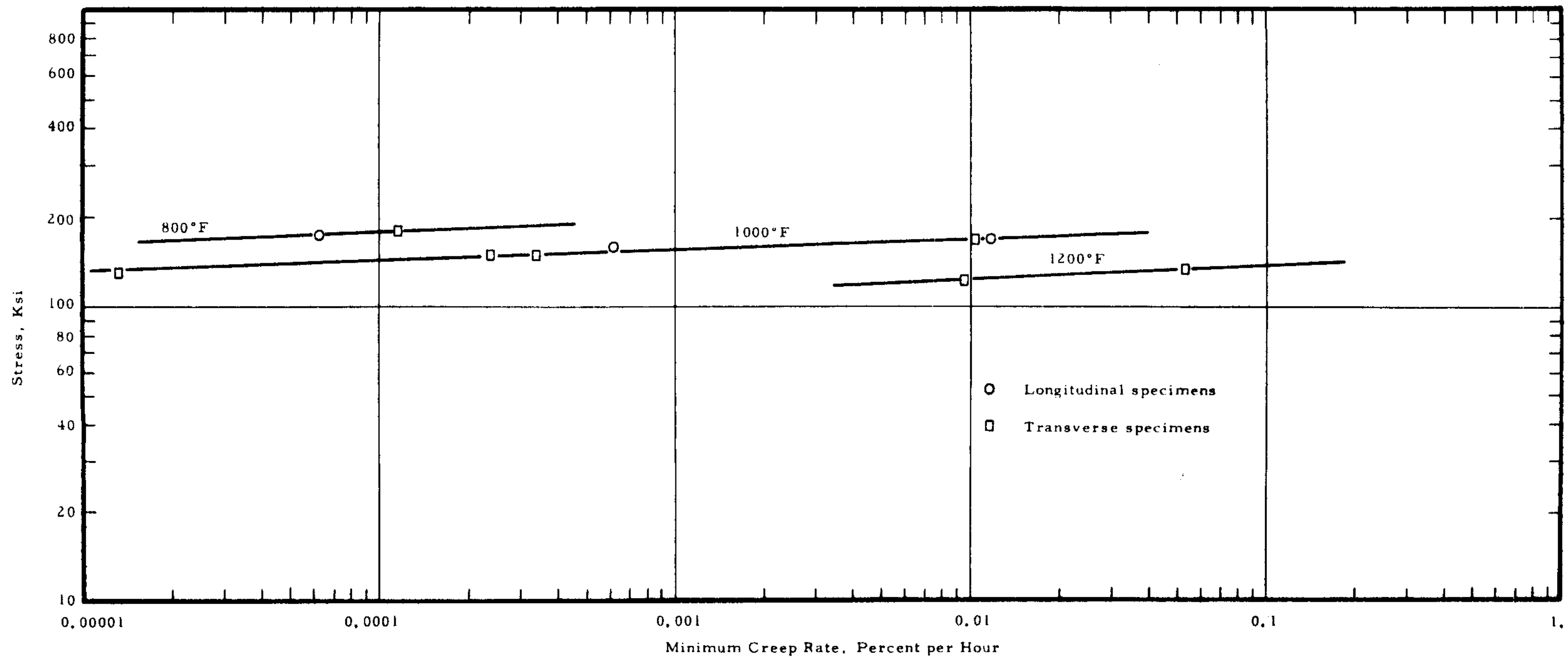


Figure 4. Stress versus minimum creep rate data for Rene' 41 in the annealed and aged condition at 800°, 1000° and 1200°F.

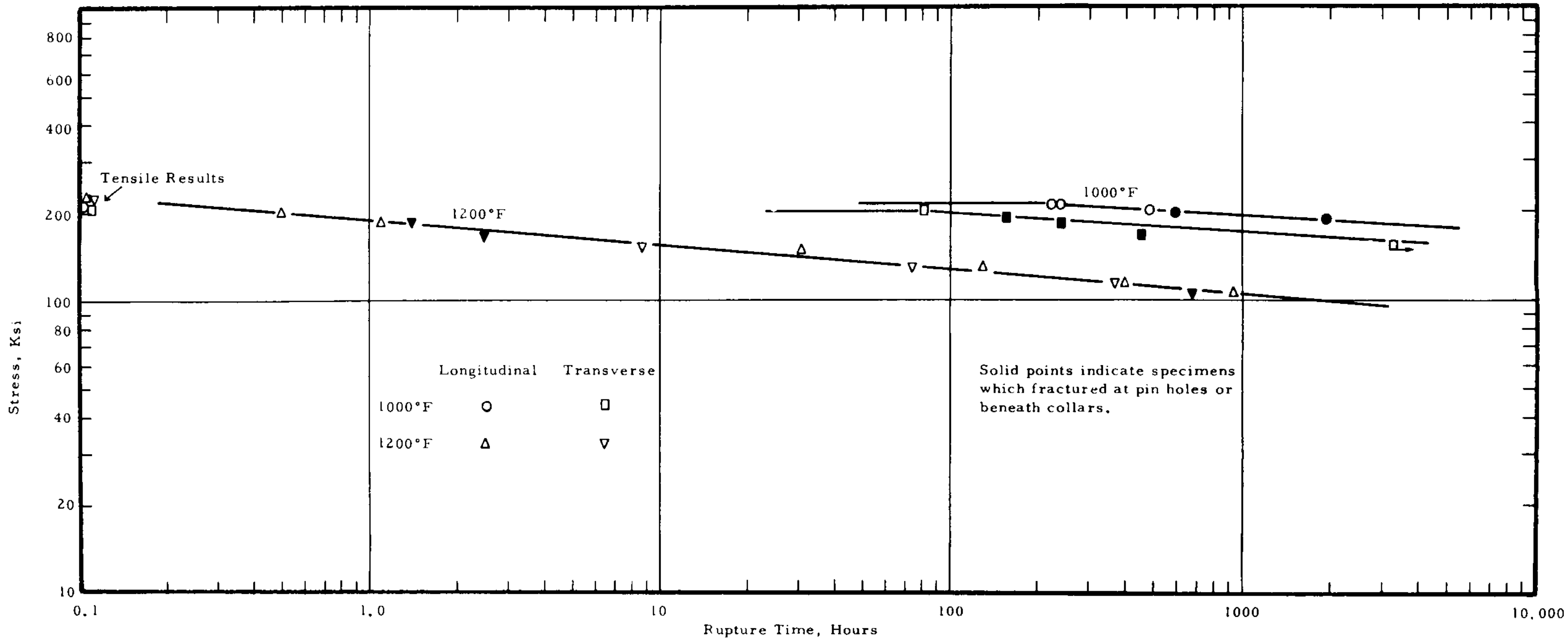


Figure 5. Stress versus rupture time results obtained from smooth specimens of Rene' 41 in the cold worked and aged condition at 1000° and 1200°F.

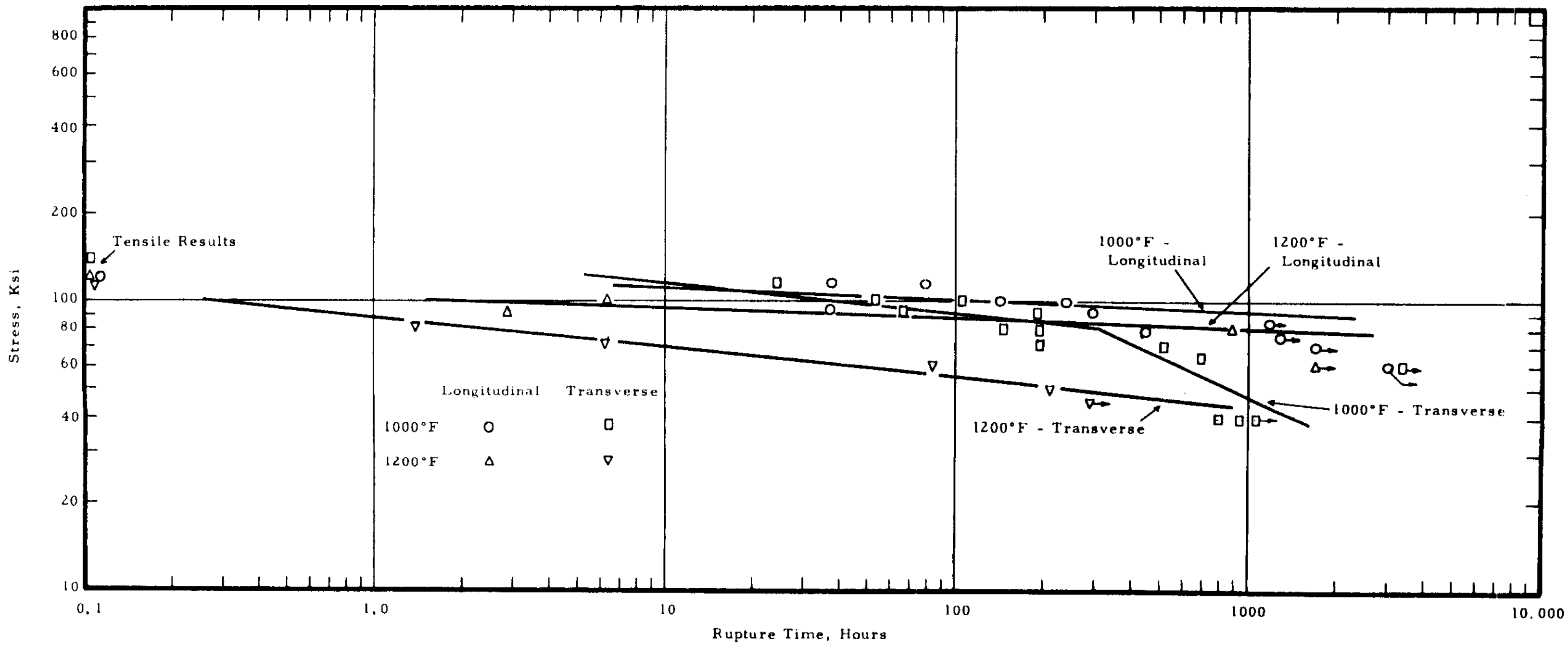


Figure 6. Stress versus rupture time data obtained from notched specimens of Rene' 41 in the cold worked and aged condition at 1000° and 1200°F.

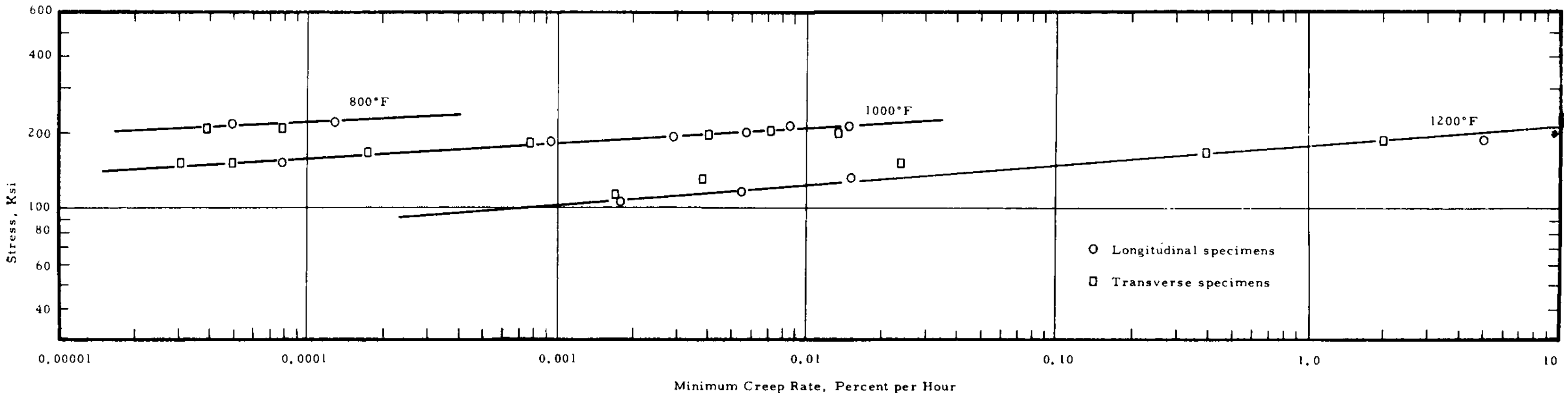


Figure 7. Stress versus minimum creep rate for Rene' 41 in the cold worked and aged condition at 800°, 1000° and 1200°F.

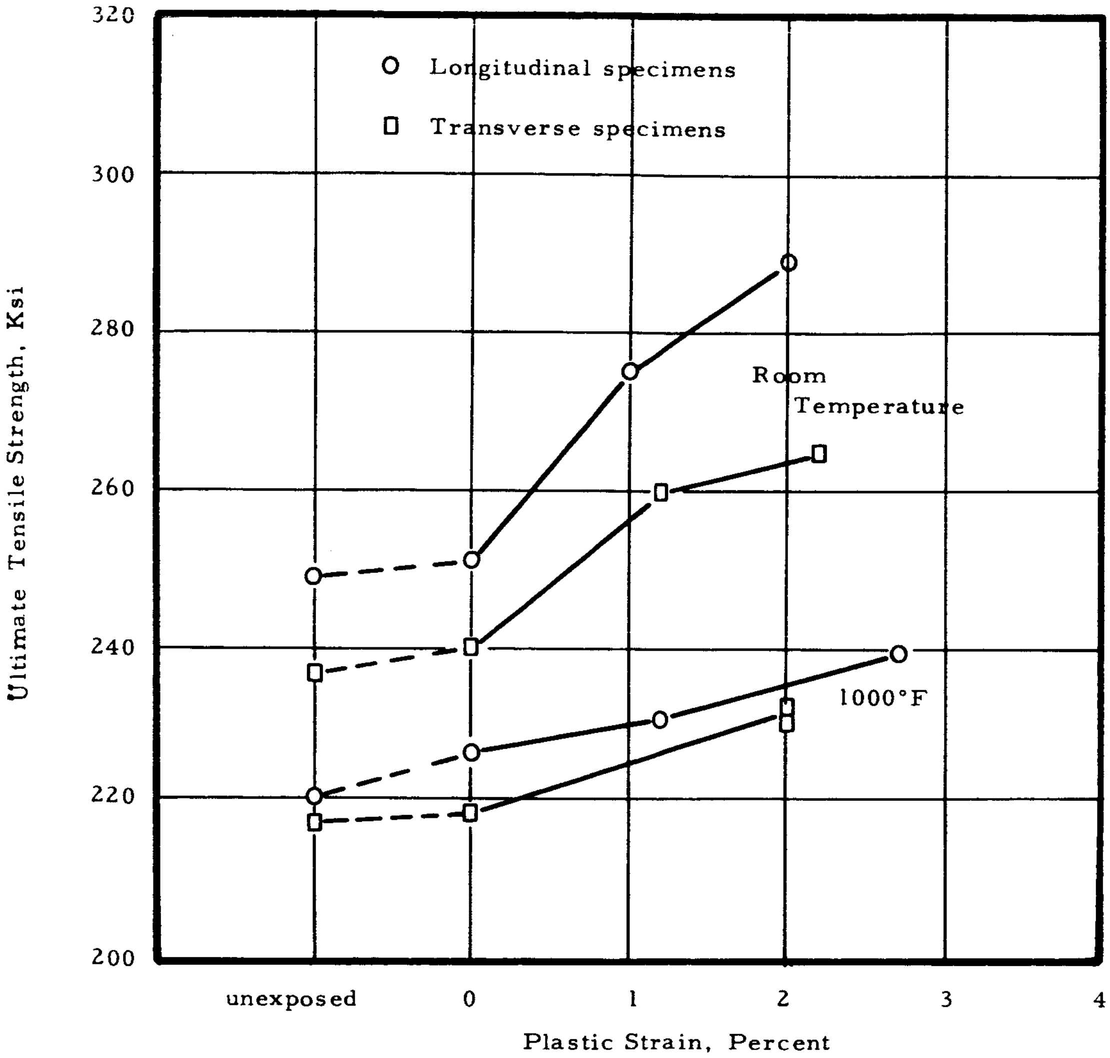


Figure 8. Influence of plastic strain introduced prior to stressed exposure on the ultimate tensile strength of Rene' 41 in the cold worked and aged condition.

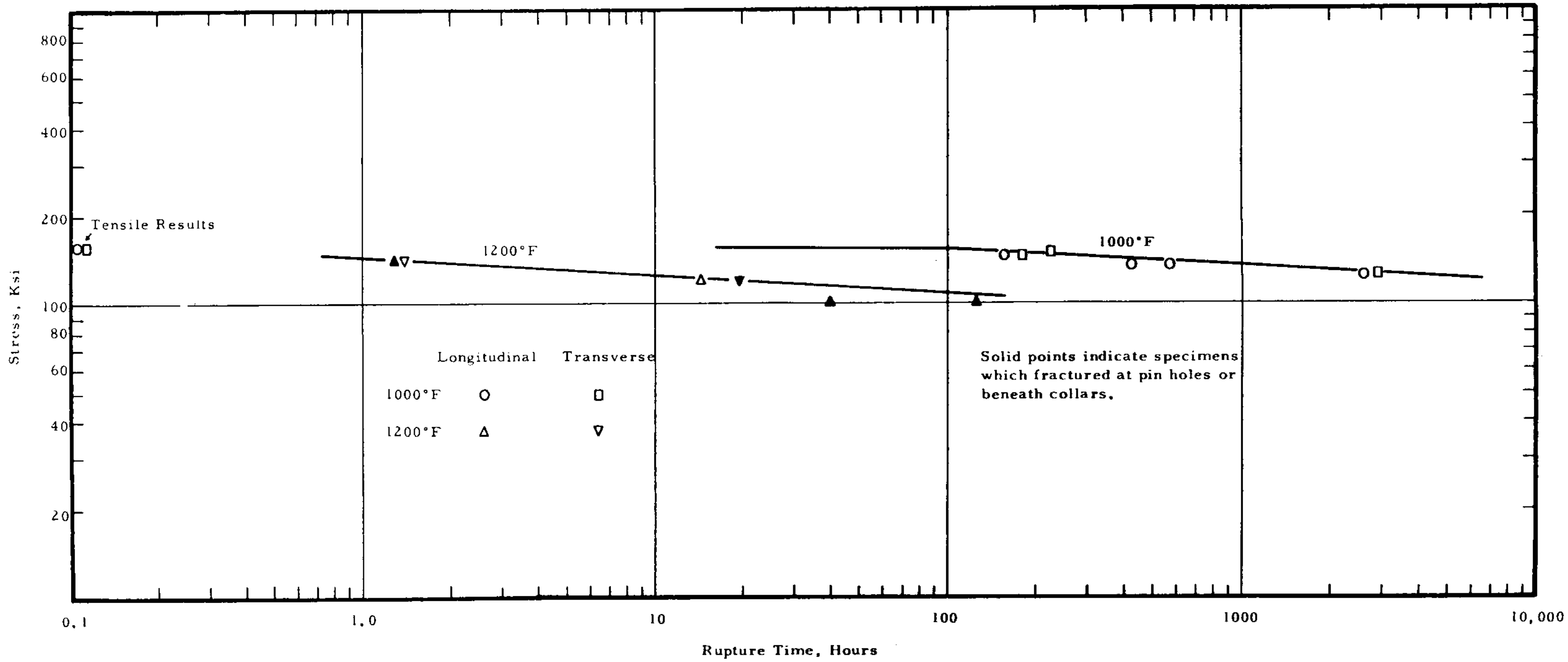


Figure 9. Stress versus rupture time data obtained from smooth specimens of Waspaloy in the annealed and aged condition at 1000° and 1200°F

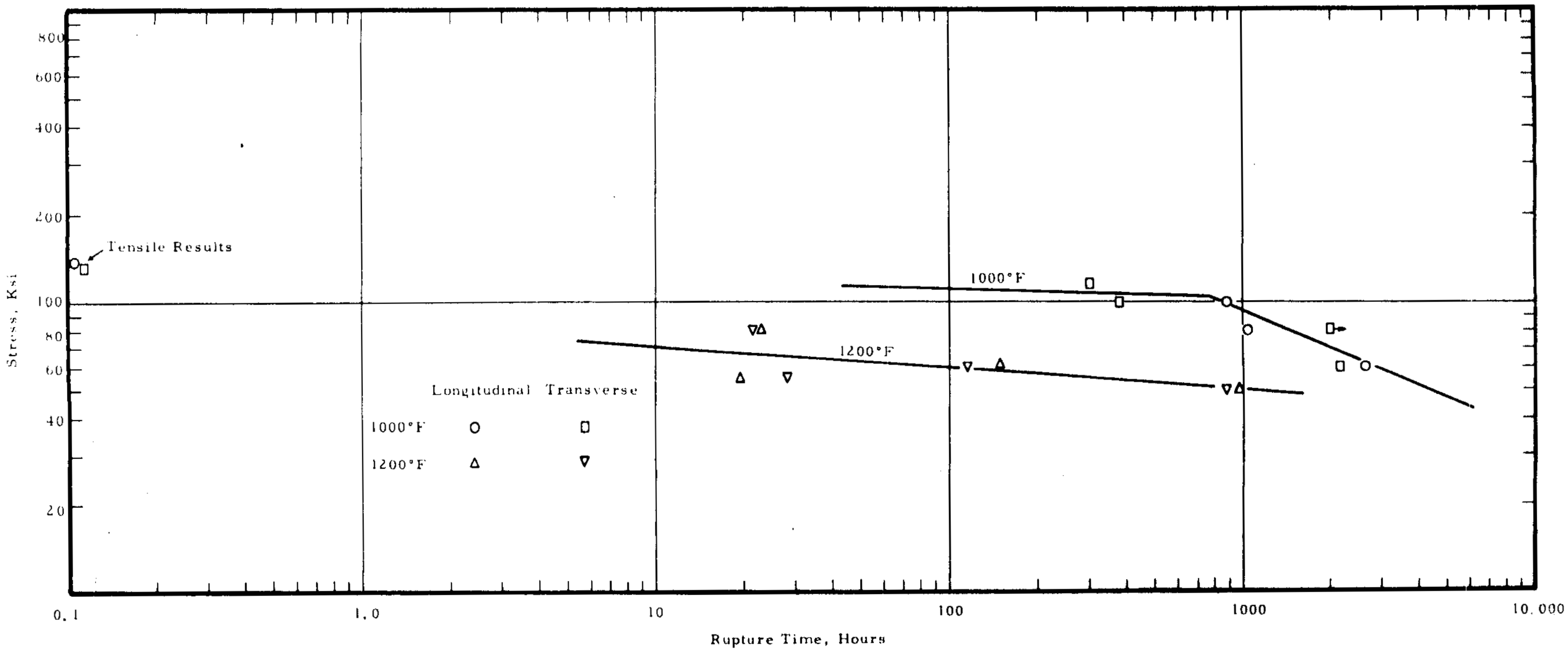


Figure 10. Stress versus rupture time data obtained from notched specimens of **Waspaloy** in the annealed and aged condition at 1000° and 1200°F.

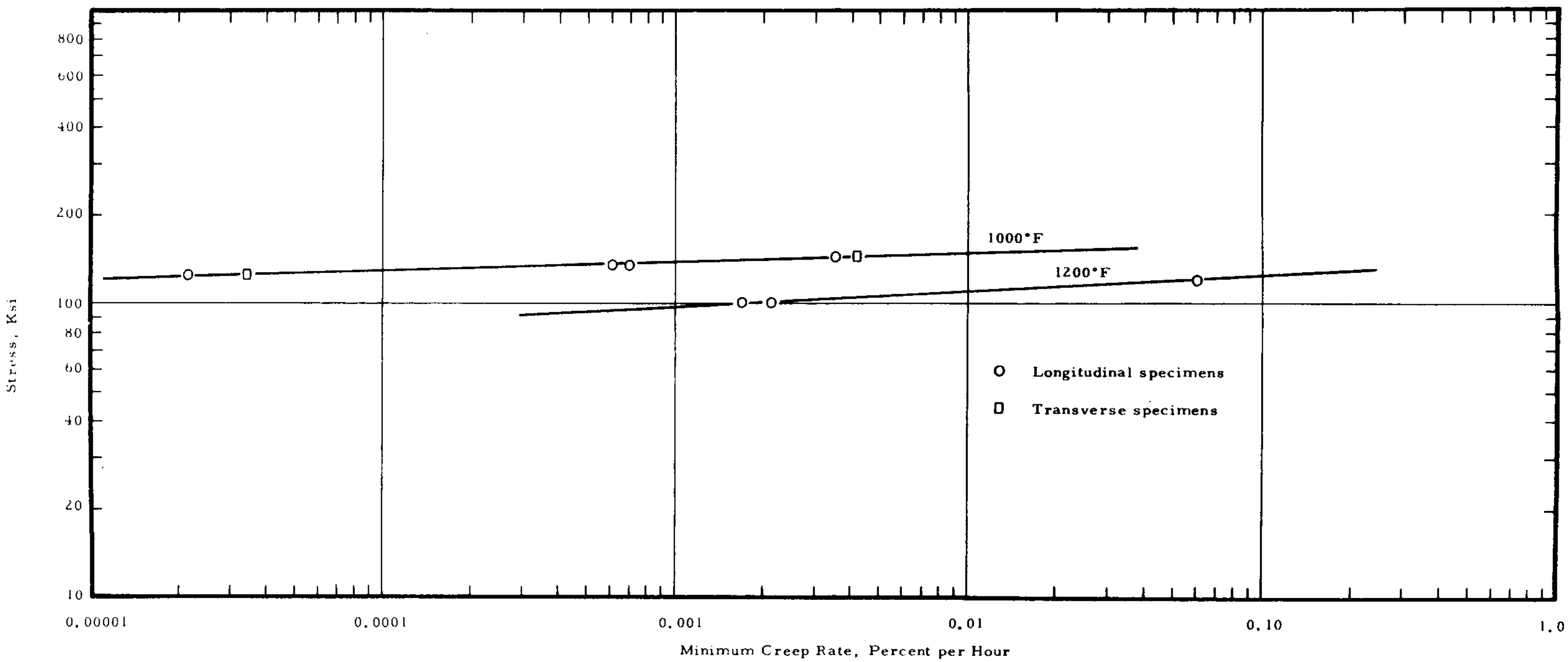


Figure 11. Stress versus minimum creep rate data for Waspaloy in the annealed and aged condition at 1000° and 1200°F.

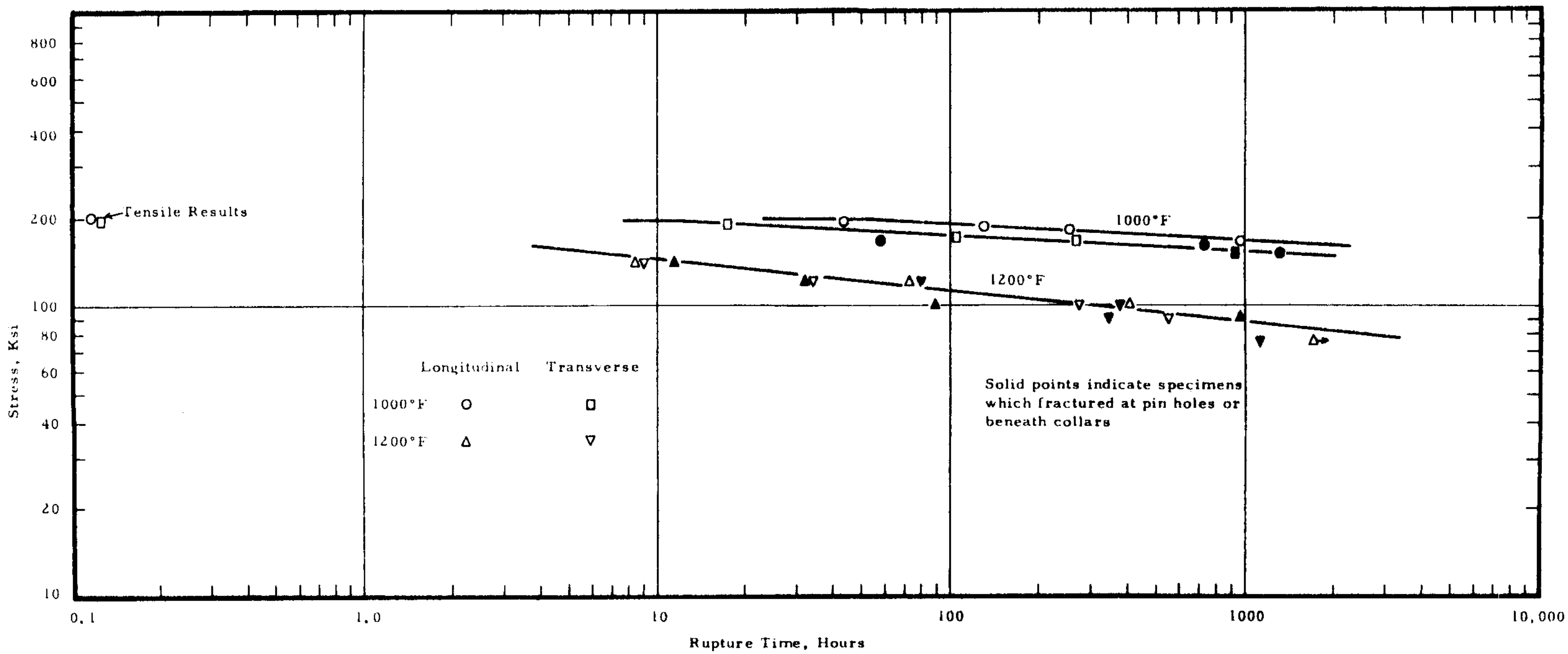


Figure 12. Stress versus rupture time data obtained from smooth specimens of Waspaloy in the cold worked and aged condition at 1000° and 1200°F.

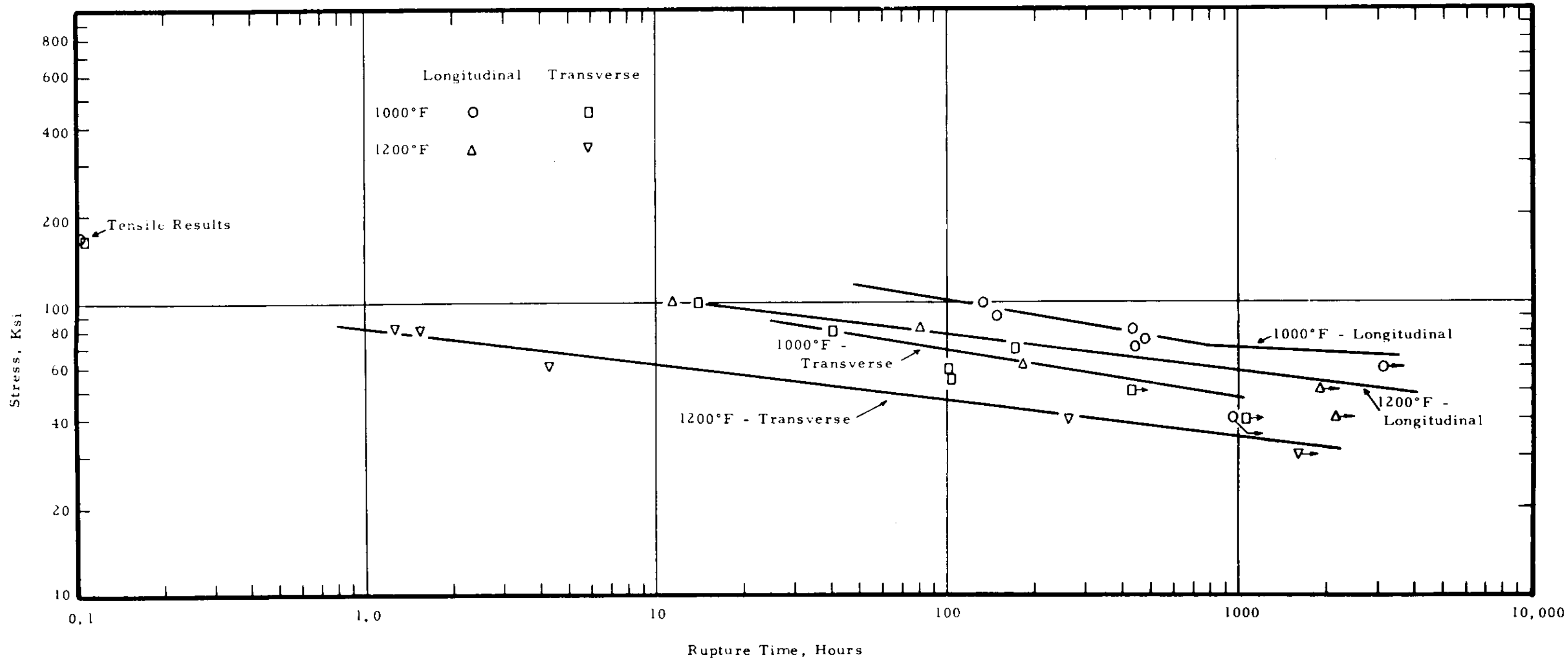


Figure 13. Stress versus rupture time results obtained from notched specimens of Waspaloy in the cold worked and aged condition at 1000° and 1200°F.

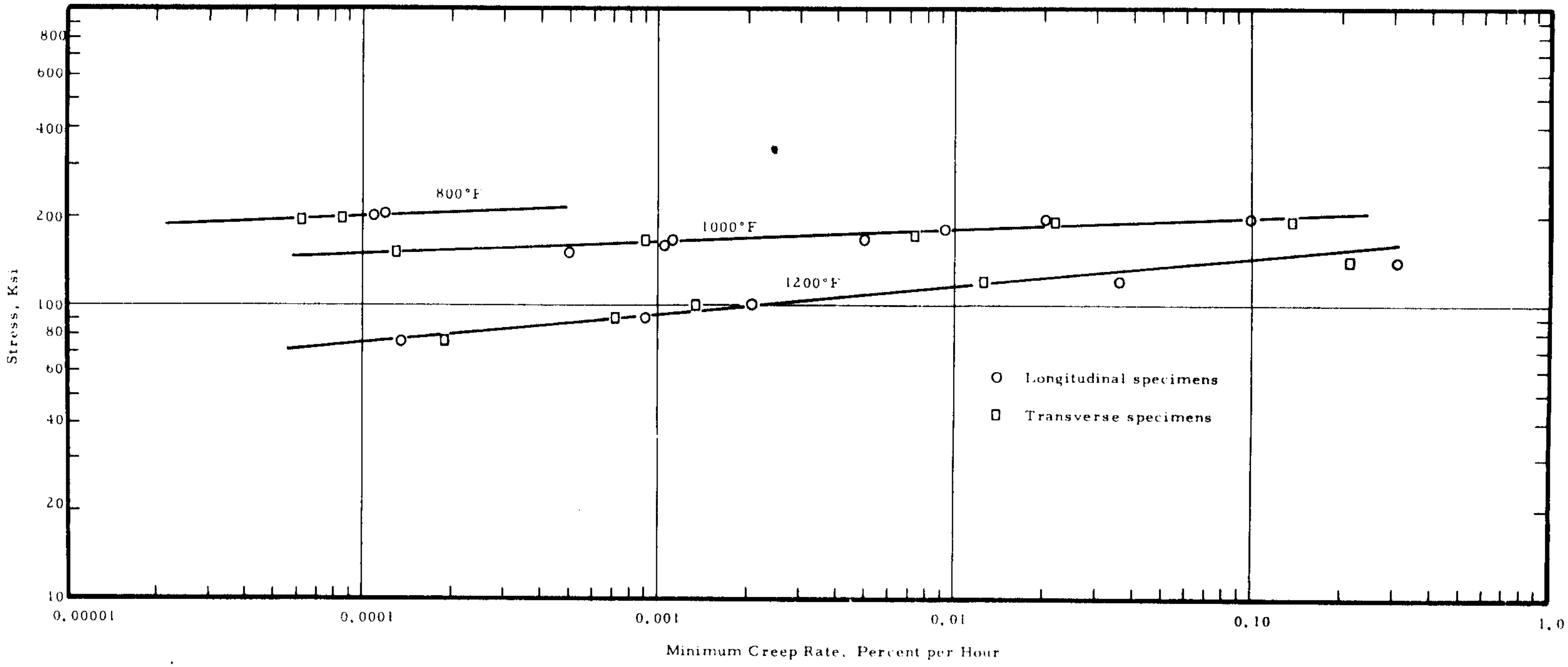


Figure 14. Stress versus minimum creep rate data for Waspaloy in the cold worked and aged condition at 800°, 1000° and 1200°F.

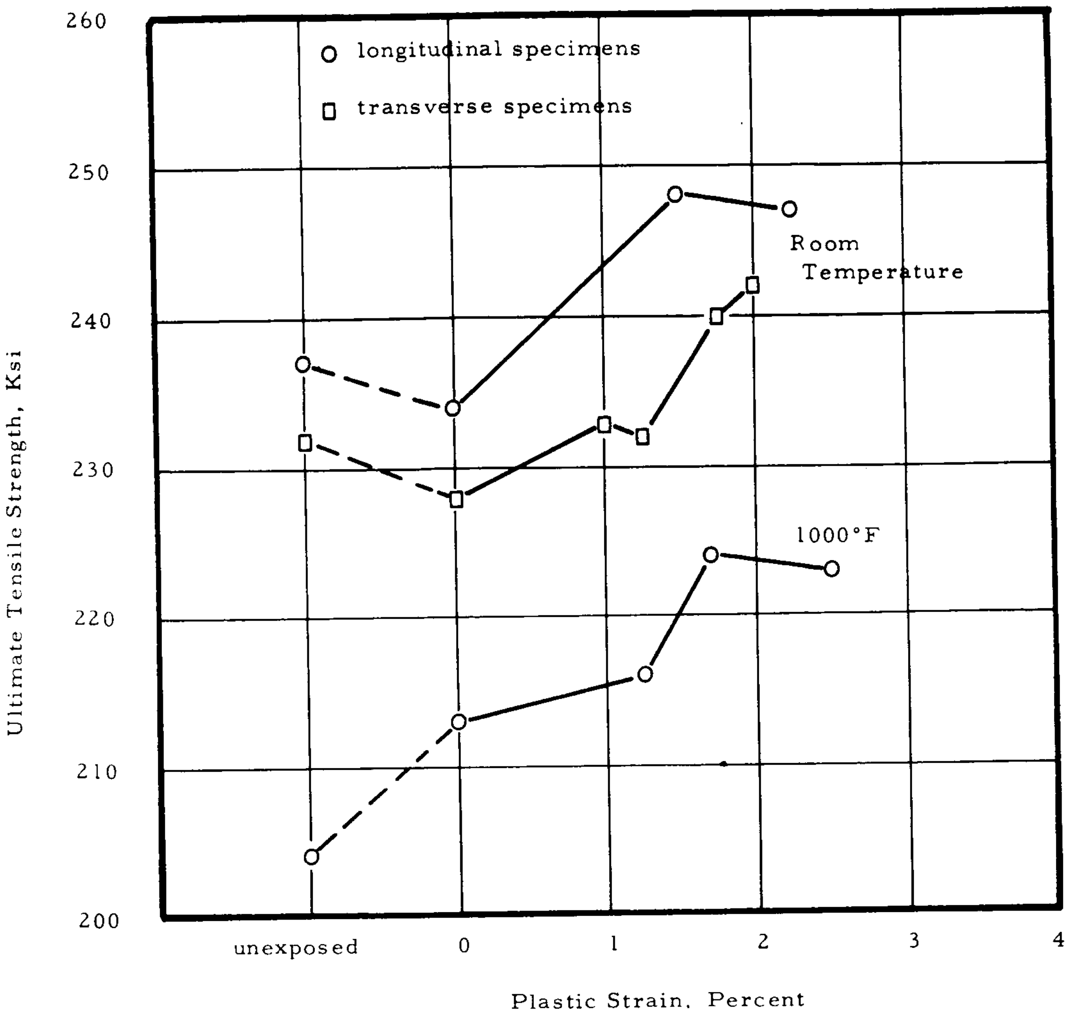


Figure 15. Influence of plastic strain introduced prior to stressed exposure on the ultimate tensile strength of Waspaloy in the cold worked and aged condition.

NASA-Langley, 1964